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Approach to Modeling and Control of Operational Modes for Chemical and Engineering System Based on Various Information

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Abstract: Method on development of mathematical models for chemical and engineering system (CES) in the conditions of deficit and illegible initial information is presented based on system approach and use of the available information sources. The method is implemented when developing models of chemical and engineering system of reforming block used for the production of high-quality gasoline. Mathematical problem definitions for control and selection of effective operating modes for chemical and engineering system are formalized and obtained on the basis of mathematical modeling. Based on principles of relative assumption and equality principles, heuristic algorithm is developed for the solution of formulated problem related to making decisions on operating modes of reactors of reforming block. Setting problems on control in the indefinite environment and heuristic algorithms for their solving are obtained by modification of various optimality principles based on theories of fuzzy sets.

Keywords: Mathematical modeling, optimality principles, chemical and engineering system, reforming block, catalisate.

1 Introduction

Uncertainty problems connected with deficit and illegibility of initial information often occur when developing mathematical models for solving problems on control of working hours for real chemical and engineering systems. The most effective approach to solve these uncertainty problems is the use of system approach, where the available information may be applied [1,4].

Processing units of oil refining industry consist of several interconnected installations. Therefore, it is necessary to have connected mathematical models of processing units built on the basis of system approach to maintain the process in optimal mode. These models should allow predicting the influence of parameters of installations on their processes, intermediate and final products as well as operation in general.

When developing mathematical models and control of different chemical and engineering system, problems of connected uncertainty and shortage of information often occur. It is suggested to apply probability theory methods and mathematical statistics for uncertainty [4,5]. However, these methods cannot be applied if uncertainty is connected with fuzziness of initial information, this is often the case in the real working conditions. In these conditions, statistical information is either unavailable or insufficient and probability theory axioms (statistical stability of researched object and repeatability of experiments under identical conditions) are not performed. Available information is sometimes the uncertain information that is the person's (decision maker - DM, expert) knowledge (experience, intuition, judgment). Effective formalization of uncertain information representing knowledge of experts on chemical and engineering system may be obtained based on methods for the expert's evaluations and fuzzy set theory (FST) [6–9].

If the decision maker and the, experts are competent, and there exists appropriate organization for their questioning; collecting and processing of uncertain information, models that include all complex interrelations with various parameters and variable complex chemical and engineering system can be built. Such models can be more informative than those developed via traditional methods. Also, they may accurately describe real chemical and engineering systems as well as problems.

Engineering objects of oil processing are considered complex chemical and engineering systems that incorporate engineering processing processes with raw materials and

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final products (e.g. oil products) that are measured by economic indicators. In the course of work, these chemical and engineering systems affect the environment and in turn it requires some ecological criteria for the evaluation of their performance. Thus, control of modes for such chemical and engineering systems should be performed taking into account economic and engineering criteria (maximize quantity of produced/made products, profit, improve engineering indicators to minimize product cost and etc.), and also criteria on ecological safety of production. To solve control multicriterial tasks with chemical and engineering system more effectively, it is necessary to turn these criteria into extreme, i.e. it is required to make decisions on the selection of optimal for operation of chemical and engineering systems. Such tasks are, as a rule, formalized in the form of problem with multicriterial choice in fuzzy environment [10,11,12]. This problem is solved on the basis of knowledge of experts and mathematical models of object which are built taking into account illegibility of initial information.

When formalizing and solving control tasks for chemical and engineering systems, some problems connected with set of inconsistent and uncertain described quality criteria may occur. When solving problems on selection of optimum operating modes and development of mathematical models for chemical and engineering systems, main sources of information are, as mentioned above, people, expert, and decision maker, i.e. their knowledge, experience, and intuitions which are expressed unclearly. This led to the emergence of new methods for the solution of the considered problems that rely on uncertain information obtained from experts in the form of their judgments about the function of an object and which incorporates their preferences in the process of decision making related to optimal control of object [11].

Successful problem resolution connected with modelling and control of chemical and engineering systems under uncertain conditions requires development of methodology on the creation of fuzzy models, further development of formalization methods, and solving problems related to the control of working modes for the system in the fuzzy environment. These represent the actual problems of chemical technology, engineering systems and processes.

The present paper aims to develop methods for construction of mathematical models for chemical and engineering system in the conditions of uncertainty, formalization of definitions for multicriterial problems related to optimal modes of object in the fuzzy environment, and development of heuristic algorithms for their solving.

2 Problem Definitions

Let us formulate control problem related to operating modes in the form of multicriterial optimization task using classical terms: it is necessary to maximize target function (criterion) $f(x)$ taking into account different restrictions $\varphi(x) \geq 0$, and $x \in X$. That is,

$$\min_x f(x),$$
$$\varphi(x) \geq 0,\ x \in X$$

where $f(x) = f_1(x),..., f_m(x)$ vector of criteria, $\varphi(x)$ denotes restriction functions, and $x = (x_1, ..., x_n)$ variables for conditions of object. Definitions range for $f(x)$, $\varphi(x)$ and x are: $0 \leq f(x) \leq f_{est}(x)$ ($f_{est}(x)$ – preset value); $\varphi(x)^{\min} \leq \varphi(x) \leq \varphi(x)^{\max}$; $x = [x^{\min}, x^{\max}]$,

where $\varphi^{\min}, \varphi^{\max}$ are minimum and maximum restriction values, $x_i^{\min}, x_i^{\max}$ symbolize lower and upper limits for change of variables *x*.

Let us consider chemical and engineering systemof production of high-qualitygasolineas the conrol object – reforming blockofcatalyticcrackingunit Leningrad Germany LG-35-11/300-95in AtyrauOilRefinery (OR). The taskisto createmathematicalmodels, modeling, and problem definition for multicriterial control of chemical and engineering system in the conditions of uncertainty, as well as development of heuristic algorithm for its solving.

Let us formulate specific main parameters of control problems for object of research.

Results of work of any chemical and engineering system may generally be estimated via vectors of criteria of two types: volumes of produced products (oil products in our case) and quality indicators of target products. Volumes of products are defined by different indicators: general, sent, normative net product, …etc. In our case, volume of target product-catalysate is measured in m^3/hour with in the interval of $(64 \div 80)$. Some problems occur during the assessment of target product quality. Quality assessment of catalysate by one number is very difficult or impossible. In the problembelow, qualityof catalystisdefinedbythefollowing indicators:

- octanenumberof a catalysate (according to motormethodis notless than $\tilde{\geq}$ 86, i.e. fuzzyrestriction):
- fractionalcompositionofcatalysate-10% and 50% refine, and respectivelyatapproximately 70 and 115°C;
- pressureofsaturatedsteam – nomore than $\tilde{\leq}$ 500 mm ofmercury;
- resin contentin 100 ml. of gasoline – nomore than $\tilde{\leq}$ 5.0 mg.

As we can see, quality indicators of target products are assessed via fuzzy criteria or restrictions such as“not less than”, “about, approximately” or “nomore than”. During decision making and control processes atproduction place, as a rule, we want volume of target products to be*more*, and product quality to be *better*. These criteria are of ten controversial, i.e. after determination of Pareto set, it is impossible to improve them at the same time. Thus, during control of chemical and engineering system taking into accountthe situation at production place and production schedule, it is necessary to find compromise solution that satisfies requirements of the decision maker.

Thus, weformalizeproblemon selectionandcontrolfor operational modes ofchemical and engineering systemfor reforming blockandset it in a mathematical way, asfollows.

Let $f(x)=\varphi^1(f(x))=\mu_0^1(x)$ benormalizedcriterionthatasse sses output (volume) oftargetproductofreforming block – catalysate. Let us assume thatmembership functionofaccessory $\mu_q(x),\ q=\overline{1,5}$ foreachfuzzyrestriction $\varphi_q(x)\ \tilde{\geq}\ (\tilde{\approx},\tilde{\leq})b_q,\ q=\overline{1,5}$, is built and describes quality indicators of catalysate. A number of priorities for restrictions or vector of scales showing mutual importance of these restrictions $\beta=(\beta_1,\beta_2,\beta_3,\beta_4,\beta_5)$ are known.

In the conditions of multicriteriality and illegibility, formalized problem can be set in the form of problem of uncertain/fuzzy mathematical programming(FMP):

$$\max_{x\in X}\mu_0(x),\ \mu_0(x)=\mu_0^1(x) \text{ or } \mu_0(x)=\log\mu_0^1(x) \quad (1)$$

$$X=\{x: x\in\Omega\wedge\arg\max_{x\in\Omega}\sum_{q=1}^{5}\beta_q\mu_q(x)\wedge\sum_{q=1}^{5}\beta_q=1`\wedge\beta_q\geq 0,\ q=\overline{1,5}\} \quad (2)$$

The optimal solution for this problem is the vecto rregime, entrance parameters $x^*=(x_1^*,x_2^*,\ldots,x_5^*)$, which provides extreme values of criteriaI at compliance with imposed restrictions that consider and satisfy preferences of decision maker.

Criterion $f_i(x), i=\overline{1,m}$ and restrictions $\varphi_q(x),\ q=\overline{1,5}$ depend on vector of entrance, regime parameters $x_i,\ i=\overline{1,5}$: x_1 – volume of raw materials; x_2, x_3 – temperature and pressure in reactors of reforming R-4, R-4a; x_4 – rate of volume flow for raw materials: x_5 – relation of hydrogen/hydrocarbon. These dependences are defined on the basis of mathematical models of reforming process that are developed taking into account shortage and illegibility of in itial information. Let us consider the suggested system approach on the development of models and modeling chemical and engineering, system where we take reforming block of catalytic reforming unit in the Atyrau Oil Refinery as an example.

3 Method for Mathematical Modeling of Chemical and Engineering System Based on Various Sources of Information, and Development of Models for Reforming Reactor

Let us consider mathematical statement for every local criterion $f_i(x), i=\overline{1,m}$, i.e. method for building mathematical model [12,13,14] that describes dependence of output parameters of chemical and engineering system for production of gasoline on its mode parameters, where we consider the available information.

Suggested method for modeling chemical and engineering system on the basis of the available information involves the following aspects:

1. Research of chemical and engineering system elements, connections between elements, collecting and processing the available informandtion, and determination of the purpose of modeling;
2. Determination of assessment criteria and comparison of models which are possible to be built for the elements of the system taking into account purpose of modeling;
3. Adopting the chosen criteria to carry out the expert evaluation of the possible models for each chemical and engineering system element based on the selected criteria and define optimal type of model for each element;

3.1 If theoretical data are sufficient for description of operation of chemical and engineering system element and summarized assessment criteria for building a model are effective, determined models are built for such unit based on analytical method;

3.2 If statistical data are sufficient for the description of operation of chemical and engineering system element or collection of such data is possible and statistical model is effective based on summarized assessment criteria and comparison, statistical models of this element are built based on experimental and statistical methods;

3.3 If theoretical and statistical data are insufficient for the description of operation chemical and engineering system elements; collecting of such data is economically impractical; and collecting uncertain information that describes operation and processes unit is possible, uncertain model is effective according to summarized assessment/comparison criteria, then uncertain models should be built for such units based on FST; for these purposes see point 4;

3.4 If theoretical data, statistical data, and uncertain expert information for the description of the object operation are insufficient and collecting such data is useless, *combined model* should be built for such unit on the basis of combined information (theoretical, statistical, unclear) and other available data. For the description of different parameters of specific element of chemical and engineering system that depend on nature of information, see 3.1–3.3 or 4;

4. Determination and selection of model with uncertain input (mode) $\tilde{x}_i\in A_i,\ i=\overline{1,n}$ and output $\tilde{y}_j\in\tilde{B}_j,\ j=\overline{1,m}$ parameters. $\tilde{A}_i\in X$, $\tilde{B}_j\in Y$ – uncertain subsets, X, Y – universal sets. Input parameters can be accurate (determined) i.e. $x_i\in X_i$, $i=\overline{1,n}$;
5. If $x_i\in X_i$, i.e. input parameters of object (element of CES) are determined, determination of the structure of uncertain equations for multiple regression (polynomial equations) are $\tilde{y}_j=f_j(x_1,\ldots,x_n,\tilde{a}_0,\tilde{a}_1,\ldots,\tilde{a}_n)$, $j=\overline{1,m}$ (solution of problem for structural identification);

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6. On the basis of expert methods for the description of chemical and engineering system element and determination term sets of uncertain parameters $T(X_i, Y_j)$;

7. Building membership function (MF) of uncertain parameters $\mu_{A_i}(\tilde{x}_i), \mu_{B_j}(\tilde{y}_j)$. For building membership function, e.g. output parameters of object, it is suggested to use the following formula (3)

$$\mu_{B_j}^p(\tilde{y}_j) = \exp(Q_{B_j}^p \left|(y_j - y_{mdj})^{N_{B_j}^p}\right|) \quad (3)$$

where $\mu_{B_j}^p(\tilde{y}_j)$ – is membership function (MF)of uncertaininputparameters $\tilde{y}_j$ that belong touncertainset $\tilde{B}_j$, p denotes quantum number (interval), $Q_{B_j}^p$ – is parameter which is defined at identification of membership function and characterizing degree of fuzziness, $N_{B_j}^p$ – coefficient that changes range of definition of terms and form of schedule for membership function fuzzy parameters; y_{mdj}^p denotes fuzzy variable that is mostcorrespondingtosetterm (inquantum$p$)forsuch value $\mu_{B_j}^p(y_{mdi}) = \max_j \mu_{B_j}^p(y_j)$;

8. If input and output parameters of chemical and engineering system element are fuzzy, we need to formalize fuzzy R_{ij} that defines connections between $\tilde{x}_i$ and $\tilde{y}_j$. Build linguistic models and see point 10;

9. If conditions of point 5 are followed, then estimate values of fuzzy coefficients $(\tilde{a}_0, \tilde{a}_1, ..., \tilde{a}_n)$ identified in point 5 of models $\tilde{y}_j$ (solution of problem with parametric identification) and see point 11;

10. If conditions of point 8 are followed, then based on rules of composition input $B_j = A_i \circ R_{ij}$,carry out determination of fuzzy parameter values for the object:

$$\mu_{B_j}^p(\tilde{y}_j^*) = \max_{x_i \in X_i}\{\min[\mu_{A_i}^p(\tilde{x}_i^*), \mu_{R_{ij}}^p((\tilde{x}_i^*, \tilde{y}_j)]\} \quad (4)$$

If $\tilde{x}_i^*$ – parameter values of object estimated by experts, then set of current values of input parameters is defined as fuzzy set consisting of maximal values of membership function $\mu_{A_i}(\tilde{x}_i^*) = \max(\mu_{A_i}(\tilde{x}_i))$.

Membership functions of p-quantum (interval) of fuzzy values for output parameters of modelled object $\mu_{B_j}^p(\tilde{y}_j^*)$ are calculated according to formula (4)

Numerical values of output parameters of object $\tilde{y}_j^{**}$ are defined out of set of fuzzy solutions according to the following formula: $\tilde{y}_j^{**} = \arg\max_{\tilde{y}_j^*} \mu_{B_j}^*(\tilde{y}_j^*)$, i.e. parameters for membership function that reached maximum values.

11. Checking sufficiency of model. If sufficiency condition is satisfied: i.e. $R = |y_m - y_e| \leq R_D$, where R, R_D, criterion and its allowed value y_m and y_e, respectively, values of output parameters received are according to the model and experimentally; at identical values of input parameters, then developed models are recommended for research and determination of optimum operating modes for chemical and engineering system elements and system in general. Otherwise, it is necessary to detect the reason fo insufficiency and return to corresponding points for solving the issue with sufficiency of the model.

Experimental, statistical and expert data were collected and processed based on a method of consecutive inclusion of regressors using prior information and above mentioned method (points 2 and 3). Structure of model is defined (structural identification of models) for reforming reactors in the form of system of equations with multiple regression (5)–(7), (9) and system of fuzzy equations with multiple regression (8):

$$y_{R2} = a_0 + \sum_{i=1}^{5} a_1 x_1 + \sum_{i=1}^{5}\sum_{k=i}^{5} a_{ik} x_i x_k \quad (5)$$

$$y_{R3} = a_0 + \sum_{i=1}^{5} a_1 x_i + \sum_{i=1}^{5}\sum_{k=1}^{5} a_{ik} x_i x_k \quad (6)$$

$$y_{R4} = a_0 + \sum_{i=1}^{5} a_1 x_i + \sum_{i=1}^{5}\sum_{k=i}^{5} a_{ik} x_i x_k$$

$$y_{R4a} = a_0 + \sum_{i=1}^{5} a_1 x_i + \sum_{i=1}^{5}\sum_{k=i}^{5} a_{ik} x_i x_k \quad (7)$$

$$\tilde{y}_j = \tilde{a}_{0j} + \sum_{i=1}^{5} \tilde{a}_{ij} x_{ij} + \sum_{i=1}^{5}\sum_{k=i}^{5} a_{ijk} x_{ij} x_{kj},\ j = \overline{1,5} \quad (8)$$

$$y_j = a_{0j} + \sum_{i=1}^{5} a_{ij} x_{ij} + \sum_{i=1}^{5}\sum_{k=i}^{5} a_{ijk} x_{ij} x_{kj},\ j = \overline{6,7} \quad (9)$$

Here $y_{R2}, y_{R3}, y_{R4}, y_{R4a}$ are volume of catalysate (target product) from output of reactors R-2, R-3 and R-4 and R4a respectively; $\tilde{y}_j, j = \overline{1,5}$ is quality indicators of catalysate: octane number ($\tilde{y}_1$ – via motor method and not less than 86); fractional composition ($\tilde{y}_2$ – 10% refining – not less than 70°C, $\tilde{y}_3$ – 50% refining – no more than 115°C); pressure of saturated steams ($\tilde{y}_4$ – no more than 500 mm of mercury); resin content in 100 ml. gasoline ($\tilde{y}_5$ – no more than 5.0 mg.); $y_j, j = \overline{6,7}$ – volumes of dry gas (DG) and gas with hydrogen content (GHC); x_1 – raw materials, hydrogenate from output of hydrotreating block, m^3/hour; x_2 – volume speed in reactors, hour^{-1}; x_3 –

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temperature in reactors R-2, R-3, R-4 and R-4a at °C, x_4– pressure in reactors R-2, R-3, R-4 and R-4a in kg/cm^2; x_5 – relation of N_2/raw materials, nanometer^3; a_{0j}, a_{ij}, a_{ikj} and $\tilde{a}_{0j}, \tilde{a}_{ij}, \tilde{a}_{ikj}$, $i,k=\overline{1,5}$ – identified regression coefficients (~– fuzziness sign), free member, coefficients of linear (x_{ij}), square and mutual correlation (x_{ij}, x_{kj}).

Thus, models describing products' volumes from output of reforming block are built via experimental statistical methods in the form of models of multiple regression, and the models describing quality indicators of products are built on the basis of uncertain information obtained from experts in the form of fuzzy equations with multiple regression. Coefficients of models (5)–(9) are defined via known methods of parametric identification based on least squares method (using Regress software and MatLab system) [7].

The results of parametrical identification of models that define volumes of catalysate coming out from reactors ($y_{R2}, y_{R3}, y_{R4}, y_{R4a}$) and gas with hydrogen content (y_2) are mentioned in (10)–(13):

$$\begin{aligned} Y = {} & 0.398X_1 + 12{,}153X_2 + .032X_3 - 0.983X_4 + \\ & + 0.019X_5 + 0.005X_1^2 + 9.349X_2^2 - 0.001X_3^2 - \\ & - 0.038X_4^2 + 0.00005X_5^2 + 0.228X_1X_2 + 0.0001X_1X_3 + \\ & + 0.002X_1X_4 + 0.00049X_1X_5 + 0.037X_2X_3 - \\ & - 0.486X_2X_4 - 0.001X_3X_4 \end{aligned} \tag{10}$$

$$\begin{aligned} Y = {} & 0.395X_1 + 12.108X_2 + 0.32X_3 - 0.984X_4 + \\ & + 0.019X_5 + 0.005X_1^2 + 9.314X_2^2 - 0.00006X_3^2 - \\ & - 0.041X_4^2 + 0.00005X_5^2 + 0.229X_1X_2 + \\ & + 0.0001X_1X_3 + 0.002X_1X_4 + 0.0005X_1X_5 + \\ & + 0.037X_2X_3 - 0.504X_2X_4 - 0.00066X_3X_4 \end{aligned} \tag{11}$$

$$\begin{aligned} Y_{R4,R4a} = {} & 0.398X_1 + 11.078X_2 - 0.032X_3 - \\ & - 1.024X_4 + 0.019X_5 + 0.005X_1^2 + 9.289X_2^2 - \\ & - 0.00006X_3^2 - 0.045X_4^2 + 0.00005X_5^2 + 0.2302X_1X_2 + \\ & + 0.0001X_1X_3 + 0.0022X_1X_4 + 0.0005X_1X_5 + \\ & + 0.036X_2X_3 - 0.525X_2X_4 - 0.00068X_3X_4 \end{aligned} \tag{12}$$

$$\begin{aligned} Y_2 = {} & 500X_1 + 7142.857X_2 + 10.101X_3 - 1458.333X_4 + \\ & + 25.0X_5 + 6.25X_1^2 + 5102.041X_2^2 + 0.0204X_3^2 - \\ & - 60.64X_4^2 + 0.063X_5^2 + 178.571X_1X_2 + 0.253X_1X_3 - \\ & - 5.625X_1X_4 + 15.625X_1X_5 - 297.619X_2X_4 - \\ & - 2.525X_2X_4 - 0.0501X_3X_5 - 1.042X_4X_5 \end{aligned} \tag{13}$$

Identification of fuzzy coefficients $\tilde{a}_{ij}, i=\overline{0,6}$ and $\tilde{a}_{ikj}, i,k=\overline{0,6},\ j=\overline{3,7}$, $\tilde{a}_{ij}, i=\overline{0,6}$, $j=\overline{3,7}$ system of equations (9) is carried out on the basis of methods from the fuzzy set theory and α-sets for levels α=0.5, 0.75 (left and right) and 1.

Models that cover the output of the unit have the form of multiple regressions which are identified via experimental and statistical methods. Models that access quality of catalyst have the form of fuzzy regression equations and are built on the basis of qualitative data obtained from specialists and experts. Results obtained by means of various methods were compared and a solution that matched the results the most accurately was selected.

I proposed to regulate temperature of the process within the range of 515-520 ºC (temperature point would be selected based on composition of a processed raw material) in order to increase output of gasoline fraction. Increased output of gasoline fraction could be achieved by increasing the temperature of catalytic cracking process.

3.1 Problems with control of modes of chemical and engineering systems reforming block in the uncertain environment and solution algorithm based on principles of relative concession and equality.

Generally, only single criteriacases are considered in the known problem definitions with uncertain environment and their methods and there is no flexibility when accounting preferences of person making decisions. At the same time, as a rule, an fuzzy problem at defining stage is replaced with equivalent determined one which then results in loss of the main part of initial uncertain information [15].

In many cases quality factors (uncertain statements and judgements) are the main types of initial information and are normal for a person. Transformation of uncertain description into quantitative is not always possible or may be unnecessary. Therefore the most perspective approach is based on development of control methods adapted to human language, for qualitative factors of any nature, to human procedures for decision making where tasks are set and solved in the uncertain environment without transforming them to determined tasks, i.e. without losing available information of uncertain nature. New and combined principles of optimality that are modified for work in uncertain environment are suggested in this work for solving set control problem.

By modifying ideas of different principles of optimality for work in uncertain environment, it is possible to obtain different problem definitions for control of operational modes of chemical and engineering system in the form of fuzzymathematicalprogramming[16,17]and develop methods for their solution.

In practice, while solving real problems of optimization, it is often enough that some principles are followed with a certain concession. For such multicriterial tasks with several restrictions, it is suggested to apply new principle to criteria, i.e. the *quasimaximume principle*, and *method of ideal point for restrictions*:

$$\max_{x\in X} \mu_0^1(x), \tag{14}$$

$$X = \{x : \arg\max_{x\in\Omega} \min_{i\in I_0} \left(\gamma_i \mu_0^i(x) - \Delta_i\right) \wedge \arg(\mu_q(x) \ge \min \| \mu(x) - \mu^u \|_D, I_0 = \{2,..., m\}, q = \overline{1,L}\} \tag{15}$$

where $\|\cdot\|_D$ – applied metrics D,

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$\mu_0(x) = (\mu_1(x),..., \mu_L(x))$,

$\mu^u = (\max\mu_1(x), ,..., \max \mu_L(x))$. Optionally, it is possible to use instead of coordinates of ideal point μ^u units: μ^u = (1,…, 1). Ω – initial set for determination of variables x, I_0 –set of indexes of criteria transferred to restrictions.

In problems (14)–(15), the criterion with number 1 is maximized, other criteria are introduced into restrictions based on quasimaximume principle (*QM*), i.e. taking into account concession Δ_i, and fuzzy restrictions are considered based on modified method of ideal point (*IP*).

Here are problem definitions for selection of operating modes of chemical and engineering system with vector of restrictions based on *maximine principles* (for criterion) and *Pareto optimality* (for restrictions):

$$\max_{x\in X} \mu_0^1(x), \tag{16}$$

$$X = \{x : \arg\max_{x\in\Omega} \min_{i\in I_0} (\gamma_i \mu_0^i) \wedge$$
$$\arg\max_{x\in\Omega} \sum_{q=1}^{L} \beta_q \mu_q(x) \wedge \sum_{q=1}^{L} \beta_q = 1 \wedge \beta_q \ge 0, \tag{17}$$
$$I_0 = \{2,..., m\}, q = \overline{1, L}\}$$

In problems (16) – (17), main criterion is maximized with priority 1, other criteria are transferred into restrictions according to maximize principle, and fuzzy restrictions are considered on the basis of Pareto optimality [18].

Now, we will consider approach to formalization, solving multicriterial problems and fuzziness on the basis of modifications of the idea of relative concession and principle of equality:

$$\max_{x\in X} \mu_0^i(x),\ \mu_0(x) = \prod_{i=1}^{m} (\mu_0^i(x))^{\gamma_i} \text{ or}$$
$$\mu_0(x) = \sum_{i=1}^{m} \gamma_i \log \mu_0^i(x) \tag{18}$$

$$X = \{x : x \in \Omega \wedge \arg(\beta_1\mu_1(x) =$$
$$= \beta_2\mu_2(x) = ... = \beta_L\mu_L(x))\} \tag{19}$$

There exist two options of relative concession in (18), and it is possible to apply other options. If simple type of concession $\mu_0(x) = \sum_{i=1}^{m} \gamma_i \mu_0^i(x)$ is applied, we will obtain absolute concession. The range of fuzzy restrictionsis defined based on principle of equality.

The following heuristic algorithm for solution of formulated problem (18)–(19) is suggested on the basis of methods of experts' assessment and theories of fuzzy sets.

RC-EP algorithm:

1. Values of weight vector for local criteria ($\gamma_1,\ldots,\gamma_m$), $\sum_{i=1}^{m} \gamma_i = 1$, $\gamma_i \ge 0$, $i = \overline{1, m}$ are defined on the basis of expert methods;
2. Weight vector of restrictions is appointed values $\beta = (\beta_1,..., \beta_L)$ providing equality $\beta_1\mu_1(x) = \beta_2\mu_2(x) = ... = \beta_L\mu_L(x)$;
3. If $\mu_0(x)$ and γ are fuzzy, term sets need to be defined and membership functions have to be built;
4. Term set defines that restrictions and membership functions for application of restrictions are built: $\mu_q(x), q = \overline{1, L}$;
5. Formula describing relative concession should be selected, e.g.:

   $$\mu_0(x) = \prod_{i=1}^{m} (\mu_0^i(x))^{\gamma_i} \text{ or}$$

   $$\mu_0(x) = \sum_{i=1}^{m} \gamma_i \log \mu_0^i(x)$$ and problem of maximizing the criterion (18) in the setis solved considering equalities of restrictions (17). The current solutions are defined, as follows: $x(\gamma, \beta)$, $\mu_0^1 x(\gamma,\beta),\ldots,\mu_0^m x(\gamma,\beta)$, $\mu_1 x(\gamma,\beta),..., \mu_L x(\gamma,\beta)$.
6. Obtained solutions are presented to the decision maker. If the decision maker with these solutions, he is dissatisfied new values for weight vectors γ and/or β are appointed, i.e. their values are adjusted and return to point 3 is performed. Otherwise, we go to point 7.
7. Search solutions is terminated, and the decision maker defines final solutions: i.e. values of input-mode parameters $x^*(\gamma,\beta)$, which depend on weight vectors that provide optimal values for local criteria $\mu_0^1(x^*(\gamma,\beta)),\ldots,\mu_0^m(x^*(\gamma,\beta))$, and maximum values for membership function with adherence to restrictions $\mu_1(x^*(\gamma,\beta)),\ldots,\mu_L(x^*(\gamma,\beta))$.

4 Practical use and Discussion of Results

As an example of the implementation of the suggested approach, we will consider definitions and problem solutions for control of operational mode of reforming block of chemical and engineering system that operates at Atyrau OilRefinery. The problem on the selection of

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optimal operational mode for reforming block in the conditions of a single based on RC-EP algorithm may be solved by applying the above-mentioned results of research and on the basis of modified method of *relative concession* (RC) and equality principle (EP):

1. As in our cases, there exit's onlyone criterion, weight vector $\gamma = (\gamma_1,..., \gamma_m)$, $\sum_{i=1}^{m} \gamma_i = 1, \gamma_i \ge 0, i = \overline{1,m}$ is defined as $\gamma = 1$;

2. Let us introduce such values of weight vectoras β=(β_1, β_2,β_3,β_4,β_5) for restrictions that satisfy requirements of equality principle, i.e. $\beta_1\mu_1(x)=\beta_2\mu_2(x)=\beta_3\mu_3(x)=\beta_4\mu_4(x)=\beta_5\mu_5(x$: β= (0.2, 0.2,0.2,0.2, 0.2);

3. As in the considered problem $\mu_0(x) = \mu_0^1(x_1, x_2, x_3, x_4, x_5)$ or $\mu_0(x) = \log \mu_0^1(x_1, x_2, x_3, x_4, x_5)$, here $\mu_0(x)$ output (volume) of catalysate is accurate and $\gamma = 1$. Thus, there is no need to determine term set and build membership function. The criterion is determined according to above-mentioned

(12) $\mu_0(x) = y_{R4,R4a} = f_1(x_1, x_2, x_3, x_4, x_5)$.

4. Let us define term set describing uncertain restrictions and for the assessment of their degree of application, we build membership functions for their application: $\mu_q(x), q = \overline{1,5}$. As a result of expert assessment and with the help of decision maker, and experts, the following fuzzy descriptions are selected for describing restrictions: $\mu_1(x) =$ (octane number of catalysate according to motor method *is notless* than $\tilde{\ge}$ 86); $\mu_2(x) =$ (fractional composition of catalysate, 10% refining, at *approximately* $\approx 70^o$ C); $\mu_3(x) =$ (fractional composition of catalysate, 50% refining, at *approximately* $\approx 115^o$C); $\mu_4(x) =$ (pressure of saturated steam – is *no more than* $\tilde{\le}$ 500 mm of mercury); $\mu_5(x) =$ (resin content in 100 ml. gasoline – is *no more* than $\tilde{\le}$ 5,0 mg) in which term-set is identified. Now, applying identified sets, we build membership functions describing extents of accomplishment of fuzzy restrictions $\mu_q(x), q = \overline{1,5}$. These membership functions are built using formula (3) on the basis of the method suggested in the paper [19]:

$$\mu_1(x) = \exp(0.83 | y_1 - 87 |^{0.75});$$

$$\mu_2(x) = \exp(0.75 | y_2 - 69 |^{0.85});$$

$$\mu_3(x) = \exp(0.12 | y_3 - 114 |^{0.50});$$

$$\mu_4(x) = \exp(0.51 | y_4 - 500 |^{0.25});$$

$$\mu_5(x) = \exp(0.15 | y_5 - 5 |^{1.50}).$$

where y_1, y_2, y_3, y_4, y_5 are assessed values of quality indicators of the model (8) after defuzzification; 87, 69..., 5 denote parameter values that most correspond to the selected term and in which membership functionis the maximum value (1); 0.83, 0.75..., 0.15 and 0.75, 0.85..., 1.50 are coefficients for the identification of membership function, for "fast" and "slow" change of a form of membership function chart.

5. We select formula describing relative concession, for example: $\mu_0(x) = \prod_{i=1}^{m} (\mu_0^i(x))^{\gamma_i}$ or $\mu_0(x) = \sum_{i=1}^{m} \gamma_i \log \mu_0^i(x)$. In our case, the problem has only one criterion, i.e. it is m=1, $\gamma_1 = 1$, $\mu_0(x) = \mu_0^1(x_1, x_2, x_3, x_4, x_5)$ or $\mu_0(x) = \log \mu_0^1(x_1, x_2, x_3, x_4, x_5)$. For definiteness, we take the first option. We maximize criterion $\mu_0(x) = \mu_0^1(x_1, x_2, x_3, x_4, x_5)$ (18) onset (19). Fuzzy restrictions are based on the results of the previous points and on set of level α that are brought to the system of accurate restrictions. Thus, fuzzy problem is brought to define of single criteria problem with normal (accurate) restrictions, where it can be solved with modification or using known methods for their solution. As a result, current results of solution appear in dialogue mode which depends on weight coefficients of restrictions: $x(\beta)$, $\mu_0^1 x(\beta)$, $\mu_1 x(\beta), \mu_2 x(\beta), \mu_3 x(\beta), \mu_4 x(\beta), \mu_5 x(\beta)$.

6. The obtained current solutions are decision maker. The results did not satisfy him/her until the fifth cycle and he/she applied new values for vectors β andmade return to point 3. On the 6th cycle, he/she was satisfied with the results and returned to point 7.

7. Searching for solution stopped, and decision maker:

- $x^*(\beta)$, values of input-mode parameters depend on weight vector of orestrictions that provides optimal value of criterion;
- optima lvalue of criterion $\mu_0^1(x^*(\beta))$ which is reachedat $x^*(\beta)$.
- maximal values for membership functions for adherence to restrictions $\mu_1(x^*(\beta)), \mu_2(x^*(\beta)), \mu_3(x^*(\beta), \mu_4(x^*(\beta)), \mu_5(x^*(\beta))$

Obtained final results are listed in Table 1.

Analysing data in the Table 1, we may accomplish the following conclusions:

1) Suggested heuristic algorithm *RC-PR* is more effective in comparison with the determined and other

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known methods;

2)When searching fo optimum operating modes for chemical and engineering system by means of theoffered algorithm; for the account and use of additional quality (uncertain/fuzzy) information in the form of knowledge, experience and intuition of decision maker, and experts who allow, without idealizing, to describe real production situations correctly, accuracy of the solution increases;

3) Suggested algorithm of optimizationin fuzzy environment (RC-PR) allowsto define values of membership function for fuzzy restrictions, i.e. to check correctness of the obtained solutions taking into account applied restrictions.

4)Results of modeling show that increased quality requirements to products reduce its volume 6 i.e. decision maker selects compromise solution between quality and quantity of catalysate.

Table 1: Comparison of the results of the suggested algorithms [17] with those of other algorithms and with experimental data obtained from the object of control.

No.	Criterionand restriction	Deterministicmethod [20]	A(O)U-PO Algorithm [21]	Suggestedalgorithm *RC-PR*	Experimental data (Atyrau OilRefinery)
1	Output (volume) of catalisate – criterion $y_{R4,4a}$, m^3/ hour	77.2	77.6	77.8	77.5
2	Octanenumberofcatalysateaccording to MT ($\tilde{y}_1$)	86	87	87	(86)[1]
3	Fractional composition ofcatalysate; 10% refining, ^{o}C ($\tilde{y}_2$); 50% refining, ^{o}C($\tilde{y}_3$).	70 115	70 114	70 114	(70)[1] (114)[1]
4	Pressure of saturated steams, mm of mercury ($\tilde{y}_4$)	500	500	500	(500)[1]
5	Resin content in 100 ml. gasoline, mg ($\tilde{y}_5$)	5.0	4.8	4.7	(5.0)[1]
6	Membership function (MF) with adherence to restrictions $\tilde{y}_1$ – $\mu_1(x^*(\beta))$	-	1.0	1.0	-
7	MF with adherence to restrictions $\tilde{y}_2$ – $\mu_2(x^*(\beta))$	-	1.0	1.0	-
8	MF with adherence to restrictions $\tilde{y}_3$ – $\mu_3(x^*(\beta))$	-	0.97	1.0	-
9	MF with adherence to restrictions $\tilde{y}_4$ – $\mu_4(x^*(\beta))$	-	0.98	1.0	-
10	MF with adherence to restrictions $\tilde{y}_5$ – $\mu_5(x^*(\beta))$	-	1.0	1.0	-
11	$x^* = (x_1^*, x_2^*, x_3^*, x_4^*, x_5^*)$ – optimalvaluesofinput-modeparameters x_1^* - rawmaterials volume; m^3/ hour.	80	80	80	80
12	x_2^* – rate of volume flowinthereactor; hour^{-1}	1.7	1.3	1.3	1.5
13	x_3^* – temperatureinreactors R-4, R-4a, ^{o}C	500	497	494	495
14	x_4^* – pressureinreactors R-4, R-4a; kg/cm^2	26	25	25	25
15	x_5^* –ratio of hydrogen/hydrocarbon	415	400	400	400

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Note: $()^l$ means that corresponding quality indicators are defined via laboratory analysis and require a lot of time, and (-) means that corresponding indicators are not defined bythis method. In the compared methods, time for search of solution is roughly the same taking into account input of necessary data or their adjustment is about a minute.

The results presented in the Table show efficiency of the suggested algorithm for solution problems related to control of chemical and engineering system operating modes in uncertain environment because it doesn't show worse results in comparison with the known methods and production, i.e. experimental data in all aspects as well as catalysate discharge results are better compared with previous studies [22-24]. Furthermore, RC-PR algorithm allows considering uncertain restrictions, and defining the accomplishment of uncertain restrictions. As we can see, while solving uncertain problem on control, full delivery of uncertain restrictions is reached: membership functions$\mu_1(x^*(\beta)),\mu_5(x^*(\beta))$are equal to 1, delivery level for uncertain restrictions $\tilde{y}_3$ and $\tilde{y}_4$ improves. Optimum modes are achieved at lower temperature inreactors R-4, R-4a (464 ^{o}C) than in other methods.

The effect of temperature on catalyst after regeneration on output and composition of cracking products for the developed model was addressed. Calculations were made with consideration of the change in temperature of the catalyst. It, in turn, corresponds to regulatory values of the installation.

5 Conclusions

System approach on the development of mathematical models for chemical and engineering system elements, based on various information, presented and justified. Definitions of problems for control of chemical and engineering system operational modes under uncertain environment were obtained in the form of problem for selecting optimal operational modes of elements of the system based on the models and via adapting optimality principles for work in uncertain environment. Mathematical definitions of initial problem are set in the form of problems with uncertain mathematical programming. Heuristic algorithm for solving formulated problem on control in uncertain environment has been developed based on principles of relative concession and equality. Novelty of the results is that tasks on selection of optimum operating modes for the object are set and solved in uncertain environment without their preliminary transformation to determinate equivalent problems. In turn, it allows to describe industrial situations under uncertain environment in a more accurate way, and to obtain effective solutions for problems related to control of operating modes of the object. The presented approaches were implemented for the creation of mathematical models and solving problems related to the selection of optimum operating modes for reforming reactors of chemical and engineering system used for the production of high-octane gasoline under uncertain conditions.

The results are theoretically promising, they widen the boundaries for solvable practical tasks, as well as allow modeling and managing operating modes of complex chemical and engineering system taking into account multicriteriality and uncertainty of initial information.

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